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Research Article

An Evaluation of Approximated PWM Switching Schemes Instigating Acoustic Noise in Inverter-Fed Induction Motors

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Abstract: This research paper presents the acoustic noise produced by a three phase motor when driven by an inverter. The inverter is operated by various traditional approximated PWM switching schemes. Experiments show that the acoustic noise from the three phase motor changes with the variation of the PWM switching scheme. The PWM switching schemes included approximated sinusoidal, approximated third harmonic injected sinusoidal, approximated trapezoidal, and approximated triangular PWM switching schemes. The approximated trapezoidal PWM switching scheme yields the least acoustic noise. This paper highlights a relationship (in graphical terms) between the current in the neutral wire and the acoustic noise observed from the motor for various switching schemes. However, the relationship between the acoustic noise and switching scheme may require further research. Furthermore, results also show that the approximated trapezoidal PWM switching scheme yields the minimum current in the neutral wire.

Keywords: AC motor drive, PWM switching schemes, machinery acoustic noise control, neutral wire current

1. INTRODUCTION

AC induction motors are generally considered as the widely used electric equipment in the industry. The accumulative acoustic noise radiated from ac induction motors has a large impact on the environmental noise pollution. Nevertheless, a low-cost and efficient method for reducing the acoustic noise from ac motors still remains a quest. Remarkably, many research papers have shown various reasons originating the acoustic noise in induction motors [1-7]. In this perspective, analog electronic filters have been proposed to reduce the acoustic noise. Such analog filters tend to remove the harmonics that create the acoustic noise [8-9]. On the other hand, significant techniques considering a variety of PWM switching schemes along with vast discussion on operating frequencies have been established to reduce the acoustic noise from ac induction motors [10-15].

This research paper will present a comparison of acoustic noise as recorded when the ac induction motor is operated by four different approximated PWM switching schemes [22]. The four different approximated PWM switching schemes have been derived from traditional PWM switching scheme [16]. The advantage of using the approximated PWM switching schemes over the traditional PWM switching schemes is the reduction in switching losses. In addition, a comparison of the neutral wire current versus the acoustic noise level for the four different approximated PWM switching schemes, is also presented and a correlation is developed.

2. EXPERIMENTAL SETUP

As shown in fig. 1, the experimental setup consists of a DC power supply, V_s, two series connected electrolyte capacitors of equal value i.e., C_1 and

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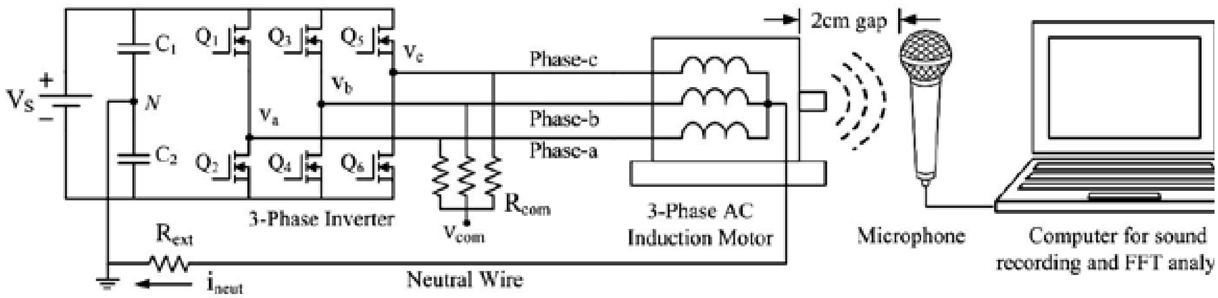


Fig. 1. The experimental setup where the DC voltage source, three-phase inverter, ac induction motor, acoustic noise recording microphone, and a computer for analysis, are shown.

C_2. Series connected electrolyte capacitors are used for reducing the voltage ripple. The common point of the two capacitors i.e., point *N* is the ground terminal. The DC voltage is fed to the three-phase inverter. The three-phase inverter consists of six MOSFETs i.e., Q_1 to Q_6. The line to ground voltages produced by the inverter, as measured from the ground terminal *N*, are represented as v_a, v_b, and v_c. Whereas the line to line voltages are represented as v_{ab}, v_{bc}, and v_{ca}. The common mode voltage found as described in [17-21], can be expressed as,

$$v_{com} = \frac{v_a + v_b + v_c}{3} \tag{1}$$

The three-phase windings of the motor are connected in Y-format. The neutral point of the motor three phase windings is connected to the ground terminal via a small resistor $R_{ext}(=1\Omega)$. The current flowing in the neutral wire is labeled as i_{neut}.

The inverter MOSFETs are controlled by a microcontroller. The microcontroller is programmed to switch the inverter for four different approximated pulse width modulation (PWM) schemes. The approximated PWM schemes include [22]:

a) 3rd Harmonic Injected Sinusoidal PWM.

b) Sinusoidal PWM

c) Trapezoidal PWM.

d) Triangular PWM.

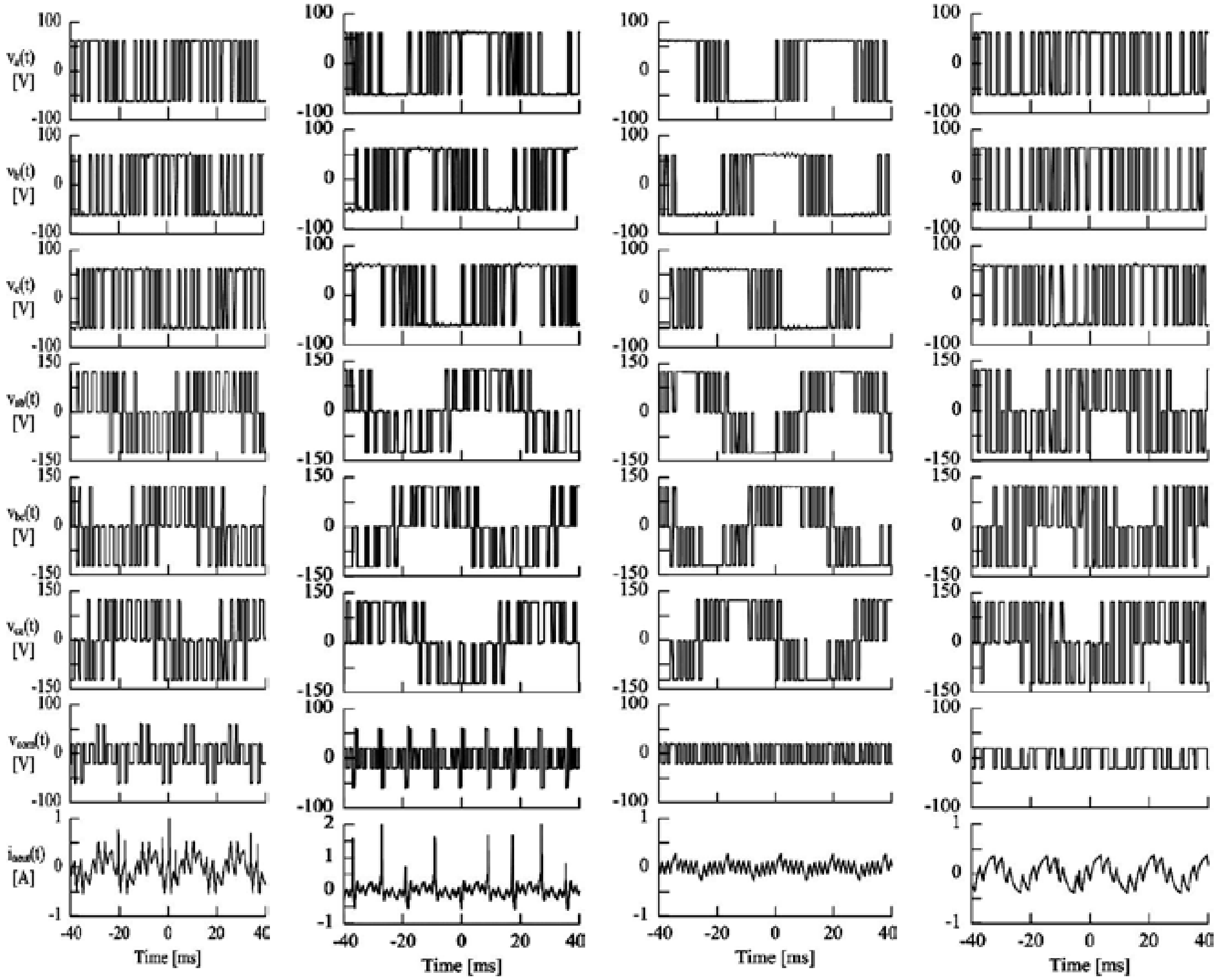
For all the above mentioned switching schemes, the microcontroller is supplied with the same carrier frequency of 1.2 kHz. A microphone, to record the acoustic noise, is placed at a distance of 2cm from the motor. The acoustic noise from the motor is recorded and stored in a computer software. The recorded acoustic noise data can be analyzed for determining the Fast Fourier Transforms (FFT). The acoustic noise is recorded while the motor is operated under no load condition.

3. EXPERIMENTAL RESULTS

The experimental results are divided into two parts. The first part presents the real-time waveforms of voltages and current for the inverter-motor systems when driven by the various approximated PWM methods. The waveforms of the voltages include line to ground voltage v_a, v_b, and v_c, the line to line voltages i.e., v_{ab}, v_{bc}, and v_{ca}, and the common mode voltage v_{com}. Whereas the waveform of the current includes the neutral wire current i_{neut}. A comparison of the common mode voltage and the neutral wire current produced from the approximated PWM switching schemes will aid in deciding the best choice for selecting the switching scheme.

The second part presents the real-time acoustic noise as recorded from the inverter-motor system while being operated under the various approximated PWM switching schemes. FFT of the acoustic noise will also be presented. A comparison of all the acoustic noise data will aid in choosing the best approximated scheme for yielding least acoustic noise.

Fig. 2(a) to (c) presents voltage waveform of the line to ground, line to line, common mode, and the waveform of the current in the neutral wire when the motor switched under the approximate 3rd harmonic injected sinusoidal PWM scheme, approximate sinusoidal PWM scheme, approximate trapezoidal PWM scheme, approximate triangular PWM scheme, respectively.



(a) (b) (c) (d)

Fig. 2 Voltage and current waveforms of the induction motor when operated under the following switching schemes, i.e., (a) 3rd Harmonic Injected Sinusoidal PWM. (b) Sinusoidal PWM. (c) Trapezoidal PWM. (d) Triangular PWM.

Figs. 3 to Fig. 6 presents experimentally obtained the acoustic noise and the FFT of the acoustic noise signals for approximate 3rd harmonic injected sinusoidal PWM scheme, approximate sinusoidal PWM scheme, approximate trapezoidal PWM scheme, and approximate triangular PWM scheme, respectively. Since the acoustic noise signal is captured by a microphone. The output of the microphone is a voltage signal that is in accordance with the acoustic noise signal. Therefore, it is to be noted the acoustic noise signals, in Figs. 3(a), 4(a), 5(a), and 6(a), are expressed in volts units. Table 1 organizes the recorded acoustic noise peak amplitude (measured in terms of volt [V]) for various approximated PWM schemes. It is seen that the Triangular PWM scheme produced the least, and 3rd Harmonic Injected Sinusoidal PWM produces the maximum acoustic noise peak amplitude.

Table 1. Peak acoustic noise for various approx. PWM schemes.

Approx. PWM Switching Scheme	**Peak Amplitude of Acoustic Noise measured in terms of volts[V]**
3rd Harmonic Inject	0.166
Sine	0.150
Trapezoidal	0.106
Triangular	0.146

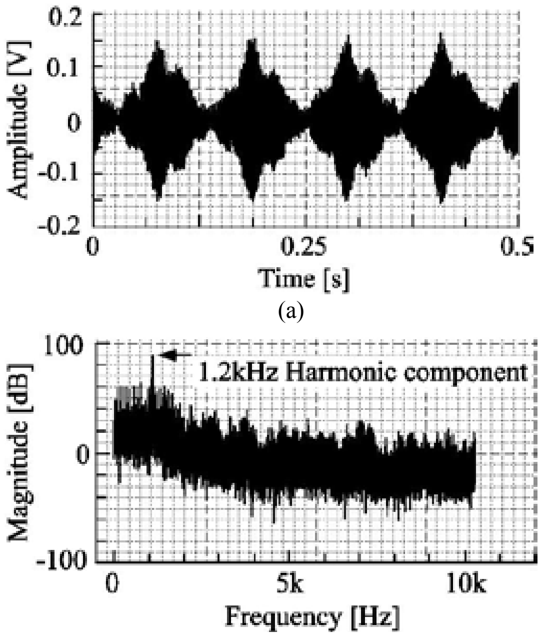


Fig. 3 Response of the induction motor switched under the 3rd Harmonic Injected Sinusoidal PWM scheme. (a) The accoustic noise signal. (b) The FFT of the accoustic noise signal.

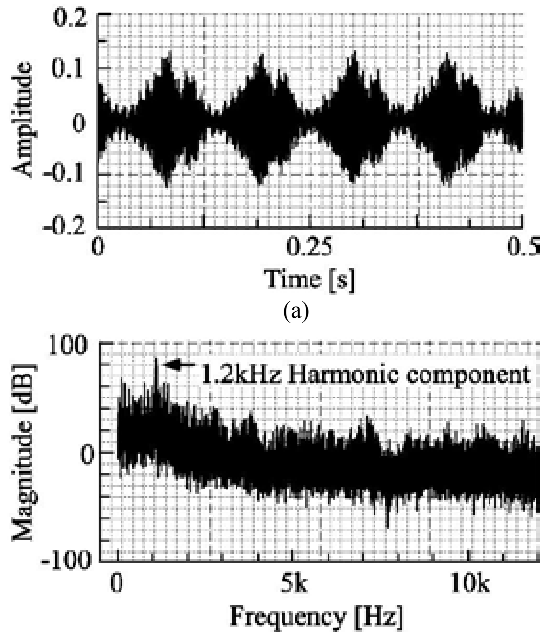


Fig. 4 Response of the induction motor switched under the Sinusoidal PWM scheme. (a) The accoustic noise signal. (b) The FFT of the accoustic noise signal.

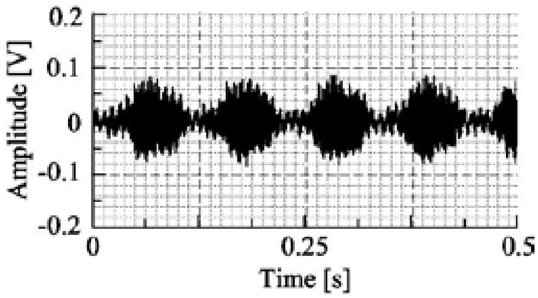
4. ANALYSIS AND DISCUSSION

Fig. 2 shows that both the common mode voltage and the neutral wire current change with the change in the switching scheme. This is in accordance to the results demonstrated in [22]. The FFT of all the approximated switching schemes, as shown in Fig. 3, show that different acoustic noise magnitude levels (expressed in dB) exist for different switching schemes. However, a 1.2 kHz harmonic component in the acoustic noise FFT response is the most prominent harmonic component found in all four switching schemes. As discussed earlier, all the switching schemes are run with the aid of the microcontroller with a carrier signal frequency of 1.2 kHz. The existence of the harmonic component having a frequency equal to that of the carrier frequency is in accordance to [3, 5, 24]. This presence of the 1.2 kHz harmonic component indicates that a notch filter can be connected between the inverter and motor to prevent the 1.2 kHz harmonic component from entering the motor. Thereby, the acoustic noise of the motor can be reduced.

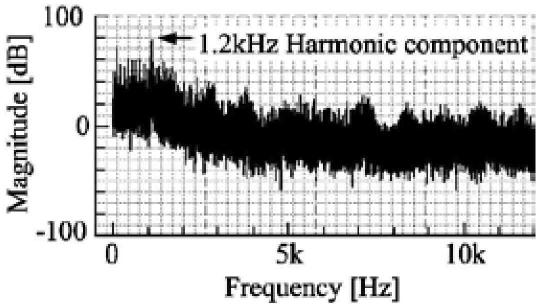
Also, a comparison of the four approximated PWM schemes as shown in Fig. 2 to the corresponding acoustic noise signals as shown in Fig. 3 to 6, illustrates that as the line to ground voltage, line to line voltage, or common mode voltage changes the acoustic noise generated from the motor. Table 2 presents the RMS common mode voltage, RMS neutral current, and RMS of Acoustic Noise, for the four approximated PWM switching schemes. Again, it is seen that the Triangular PWM scheme produces the least RMS neutral current, and RMS of Acoustic Noise. Whereas 3rd Harmonic Injected Sinusoidal PWM produced the maximum RMS neutral current and RMS of Acoustic Noise.

Table 2. RMS Values of various parameters for the four approximated switching schemes.

Approx. PWM Switching Scheme	RMS Common mode Voltage[V]	RMS Neutral Current[A]	RMS of Acoustic Noise measured in terms of volts[V]
3rd Harmonic Inject	31.77	0.238	0.053
Sine	31.59	0.214	0.045
Trapezoidal	19.63	0.103	0.031
Triangular	19.67	0.207	0.045

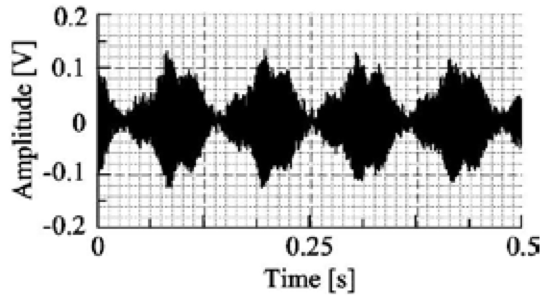


(a)

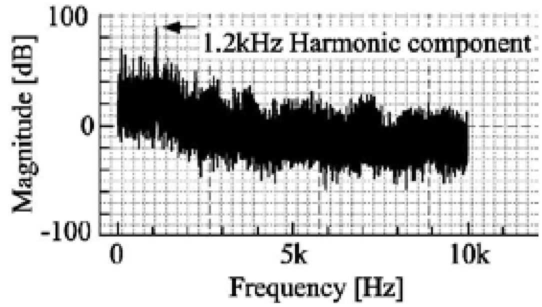


(b)

Fig. 5 Response of the induction motor switched under the Trapezoidal PWM scheme. (a) The accoustic noise signal. (b) The FFT of the accoustic noise signal.



(a)



(b)

Fig. 6 Response of the induction motor switched under the Triangular PWM scheme. (a) The accoustic noise signal. (b) The FFT of the accoustic noise signal.

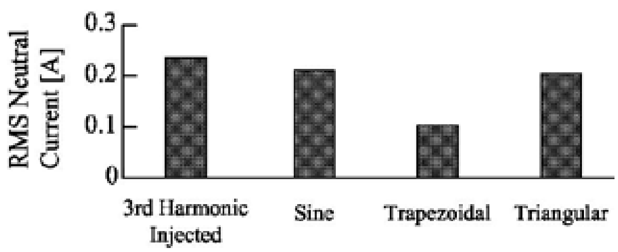


Fig. 7. Comparison of the neutral wire current as produced against the various switching schemes.

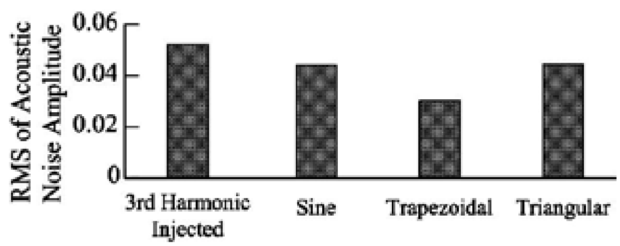


Fig. 8. Comparison of the acoustic noise produced against the various switching schemes.

Fig. 7 demonstrates in graphical arrangement, how the RMS of neutral wire current changes with the change in switching scheme. Similarly, Fig. 8 presents the change of RMS values of acoustic noise amplitude with the change in switching scheme. Comparing Fig. 7 and 8, it is interesting to note that the pattern of change of RMS neutral wire current with respect to the switching scheme is similar to the pattern of change of RMS of acoustic noise amplitude. In other words, among the four switching schemes, the 3rd harmonic injected sinusoidal PWM scheme produces the maximum neutral wire current and maximum acoustic noise, second in position is the sinusoidal PWM scheme, third is position is the triangular PWM switching scheme, whereas the least neutral wire current and the least acoustic noise is produced by the trapezoidal PWM scheme. However, the research can be extended to explain the relationship between the neutral wire current and the acoustic noise. At this stage the best choice to the least acoustic noise is to operate the motor from the trapezoidal PWM switching scheme.

5. CONCLUSIONS

This research has shown the acoustic noise characteristics for motor driven by the four approximated PWM switching schemes including 3rd harmonic injected sinusoidal PWM, sinusoidal PWM, trapezoidal PWM, and Triangular PWM. Result show that for the 3rd harmonic injected sinusoidal PWM the current in the neutral wire and the acoustic noise generated from the motor is maximum whereas for the trapezoidal PWM switching scheme the neutral wire and the acoustic noise generated from the motor is minimum. In addition, high switching frequency (above 15 kHz) is a very effective practice but levies high stress on semiconductor switching devices and amplify switching frequency losses.

6. REFERENCES

1. Wallace, A.K., R. Spée, & L. Martin. G. Current harmonics and acoustic noise in AC adjustable-speed drives. *IEEE Transactions on Industry Applications* 26: 267–273 (1990).
2. Belmans, R.J., D. Verdyck, W. Geysen, & R.D. Findlay. Electro-mechanical analysis of the audible noise of an inverter-fed squirrel-cage induction motor. *IEEE Transactions on Industry Applications* 27 : 539-544 (1991).
3. Lo, W.C., C.C. Chan, Z.Q. Zhu, L. Xu, D. Howe, & K.T. Chau. Acoustic noise radiated by PWM-controlled induction machine drives. *IEEE Transactions on Industrial Electronics* 47: 880-889 (2000).
4. Capitaneanu, S.L., B. de Fornel, M. Fadel, & F. Jadot. On the acoustic noise radiated by PWM AC motor drives. *Automatika* 44: 137-145 (2003).
5. Gieras, J.F., C. Wang, & J.C. Lai. *Noise of Polyphase Electric Motors*. CRC Press (2005).
6. Le Besnerais, J., V. Lanfranchi, M. Hecquet, & P. Brochet. Characterization and reduction of audible magnetic noise due to PWM supply in induction machines. *IEEE Transactions on Industrial Electronics* 57: 1288-1295 (2010).
7. Le Besnerais, J., V. Lanfranchi, M. Hecquet, P. Brochet, & G. Friedrich. Prediction of audible magnetic noise radiated by adjustable-speed drive induction machines. *IEEE Transactions on Industry Applications* 46: 1367-1373 (2010).
8. Ferreira, J.A., P. Dorland, & F.G. De Beer. An active inline notch filter for reducing acoustic noise in drives. *IEEE Transactions on Industry Applications* 43: 798-804 (2007).
9. Shami, U.T., M.U. Khan, M.B. Khan, T.H. Rizvi, & A. Khalid. A new method for the proposal of acoustic noise reduction in motors. *Science International (Lahore)* 26: 1687-1691 (2014).
10. Habetler, T.G., & D.M. Divan. Acoustic noise reduction in sinusoidal PWM drives using a randomly modulated carrier. *IEEE Transactions on Power Electronics 6*: 356-363 (1991).
11. Na, S.H., Y.G. Jung, Y.C. Lim, & S.H. Yang. Reduction of audible switching noise in induction motor drives using random position space vector PWM. *IEE Proceedings Electric Power Applications* 149: 195-200 (2002).
12. Cassoret, B., R. Corton, D. Roger, & J.F. Brudny. Magnetic noise reduction of induction machines. *IEEE Transactions on Power Electronics* 18: 570-579 (2003).
13. Kim, J.H., Y.G. Jung, & Y.C. Lim. Chaotic double tent mapping PWM scheme for acoustic noise reduction of motor drive. *Journal of the Korean Institute of Illuminating and Electrical Installation Engineers* 22: 71-78 (2008).
14. Binojkumar, A.C., J.S. Prasad, & G. Narayanan. Experimental investigation on the effect of advanced bus-clamping pulse width modulation on motor acoustic noise. *IEEE Transactions on Industrial Electronics* 60: 433-439 (2013).
15. Ruiz-Gonzalez, A., F. Vargas-Merino, J.R. Heredia-Larrubia, M.J. Meco-Gutierrez, & F. Perez-Hidalgo. Application of slope PWM strategies to reduce acoustic noise radiated by inverter-fed induction motors. *IEEE Transactions on Industrial Electronics* 60: 2555-2563 (2013).
16. Rashid, M.H. *Power Electronics: Circuits, devices and applications*. Pearson Education (2004).
17. Ogasawara, S., & H. Akagi. Modeling and damping of high-frequency leakage currents in PWM inverter-fed AC motor drive systems. *IEEE Transactions on Industry Applications* 32: 1105-1114 (1996).
18. Kempski, A., R. Smolenski & R. Strzeleck. Common mode current paths and their modeling in PWM inverter-fed drives. *IEEE 33rd Annual Power Electronics Specialists Conference* 3: 1551-1556 (2002).
19. Lai, Y. S., & F.S. Shyu. Optimal common-mode voltage reduction PWM technique for inverter control with consideration of the dead-time effects-part I: basic development. *IEEE Transactions on Industry Applications* 40: 1605-1612 (2004).
20. Ogasawara, S., H. Ayano, & H. Akagi. An active circuit for cancellation of common-mode voltage generated by a PWM inverter. *IEEE Transactions on Power Electronics* 13: 835-841 (1998).
21. Cha, H. J., & P.N. Enjeti. An approach to reduce common-mode voltage in matrix converter. *IEEE Transactions on Industry Applications* 39: 1151-1159 (2003).
22. Shami, U.T., & T.A. Shami. Estimation of lookup table for popular pulse-width modulation schemes based on visual inspection for ac motor drive applications. *Science International (Lahore)* 26: 649-653 (2014).
23. Malfait, A., R. Reekmans, & R. Belmans. Audible noise and losses in variable speed induction motor drives with IGBT inverters-influence of the squirrel cage design and the switching frequency. In: *Proceedings IEEE Conference Industry Applications Society Annual Meeting,* p. 693-700 (1994).